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# Promotion of grid-connected photovoltaic systems in Spain: Performance analysis of the period 1998–2008

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ABSTRACT

This paper contributes a critical view of the development of grid-connected photovoltaic systems (GCPVS) in Spain during the period 1998–2008 by looking into the different actions that were intended to promote this technology. The Spanish photovoltaic (PV) sector has undergone bullish development in the recent years, but its underlying factors still lack systematic identification and analysis. Accordingly, this paper collects and presents detailed data for describing this evolution. It also makes a special case of the particular promotion of PV systems on roof and goes further to analyze how these actions have affected GCPVS evolution as well as the magnitude of their impact on its performance. The exponential growth of installed cumulative PV power at the end of this period, which largely exceeded the target set for 2008, is canvassed by building an analogy with feedback control systems. In this approach, market response or the PV power attained is considered as the system output, while the different regulation changes are regarded as control actions aimed at enabling GCPVS to hit the energy target. Such an analysis allows determining the most significant delays and control actions that explain the system's performance. Hence, this study suggests an alternative framework to support the formulation and assessment of energy policy as it puts the emphasis not only on the evolution of the system *per se* but rather on the performance of the system against the energy target. In this regard, it might contribute to enhance the promotion mechanisms of green technologies.



**Contents**



*Abbreviations:* RES-E, electricity from renewable energy sources; PV, photovoltaic; SR, Special Regime; RD, Royal Decree; CNE, National Energy Commission; RIPRE, Special Regime Power Plants Register; PFER, Plan for the Promotion of Renewable Energy 2000–2010; PER, Plan for the Promotion of Renewable Energy 2005–2010; INE, the Spanish National Institute of Statistics; CCAA, autonomous regions or Regional Government; AET, average electricity tariff; FIT, feed-in tariff; IRR, internal rate of return; MITyC, Ministry of Industry, Tourism and Commerce; FHEPMP, final hourly electricity production market price; FAHEPMP, final average hourly electricity production market price.

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## 1. Introduction

The Spanish energy policy addressed to promote electricity from renewable energy sources (RES-E) has been praised for its excellent results, especially in the wind and photovoltaic (PV) power sectors [1]. In 2008, Spain alone accounted for 45% of the PV new capacity installed worldwide, rising from a trifling 26 MW in 2005 to an impressive 2.511 MW that year [2]. This astonishing growth has its origins in the Special Regime (SR) enforced by means of the Royal Decree 2818/1998 (RD 2818/1998) and the decision of the Spanish government to implement the feed-in tariff (FIT) promotion mechanism to encourage the use of RES-E. Since its enforcement in 1998, the SR has been in the focus of a series of studies [3–9].

Recent studies in the field of RES-E have tackled diverse aspects of PVS development and from different perspectives (e.g. legal, technical and economic) [10–14]. So far, however, there are no specific studies on the analysis of the main reasons behind the evolution of the grid-connected PV systems (GCPVS) in Spain albeit the spectacular results accrued in 2008. This is particularly noticeable if compared with the greater dynamics observed by research studies on the wind power sector [15–18].

Following the recent works of de la Hoz, del Río and del Río and Unruh [19,9,20], this study draws on control theory principles to analyze the reasons for the systematic growth of PV in the last ten years to 2008. Accordingly, based on public data available from the Bulletin of the State (BOE), the National Energy Commission (CNE) and other Governmental agencies, the PV legal, economical and technical frameworks are analyzed and described in control terms by developing an analogy with control theory principles. Certainly, the system is too complex to be easily modelled and simulated, but the parallelism of the concepts between the legal framework structure and the control structure has demonstrated to provide useful tools for identifying and describing the elements that have made the system response unstable as well as the reasons for its instability (see Section 2).

Hence, the effects of control actions on PV performance stemming from different legal and administrative decisions are discussed and conclusions are raised. Besides, the perturbations introduced in the system by the control structure have been studied and the effects on its evolution fully explained (see Section 3).

One particularly relevant outcome of this methodology was its ability to identify the misalignment between the economic framework shaped by the legislation and the effective joint use of the grid infrastructure which have prevented a better performance of on roof PV systems. Likewise, it has proven useful to disclose other side effects of the legislation such as the phenomenon of "atomization" unleashed among the PV energy producers (see Section 4).

Finally, all the factors or change drivers deemed relevant for the evolution of the PV sector during the period of analysis are duly systematized and a few conclusions are raised (see Section 5).

## 2. The energy policy control

### 2.1. Photovoltaic energy policy results

The energy policy concerning GCPVS has had two main targets[1]:

- First target or installed cumulative PV power: although expressed in different ways, this objective has been formulated explicitly in all royal decrees and in several development energy plans as the goal to reach.[2] The validity of the related economic framework depended on the achievement of this objective.
- Second target or promotion of PV systems on roof: although the promotion of GCPVS on roof was not explicitly defined in the law, it was the second major objective. Since the SR came into force under the Law of the Electricity Sector (Law 54/97), PV systems had a very favourable economic treatment due in part to their lack of profitability but also because they were reckoned the paradigm of distributed generation, particularly those located on roof. Initially, GCPVS on roof were assigned a rated power up to 5 kW[3] and granted the highest remuneration amongst all PV categories.

Concerning the first objective, the unexpected increase of the installed cumulative PV power in recent years—exceeding by far the targets set in both the RD 661/2007 and the Plan for the Promotion of Renewable Energy 2005–2010 (PER, see Tables 1–7)–can be considered as a complete failure from the point of view of the energy policy. For instance, although the energy generated by GCPVS exceeded the targets of PER 2005–2010, the share of PV energy in the total energy supplied in 2008 was only 0.9%. This value increases to 3.5% when the SR is taken as the reference framework, but there are still significant differences when comparing the share of PV systems in terms of produced energy with that expressed in terms of the cost of the regulated activity, which in 2008 was of 26% (see Table 3).

On the other hand, according with the economic ratios proposed in the PER 2005–2010, the multiplier effect on the economy as a whole of the outstanding growth of GCPVS installations in the years 2007 and 2008 (see Tables 4 and 5)[4] shall be especially highlighted.

Also, in reference to its contribution to the protection of the environment, GCPVS have helped to prevent the emission of no

[1] However, other goals have also been considered. The policy of promoting the SR, and the PV industry in particular, also pursued the formation of a modern sector grounded on a solid and stable industrial basis, with strong growth rates and a large market [21,22], as well as the increase of exports and qualified employment, and the improvement of regional economies' competitiveness.

[2] RD 2818/1998 (Arts. 21 and 28.1); RD 436/2004 (Art. 33.4); and RD 661/2007 (Art. 37).

[3] GCPVS <fn0015>belonging to users who previously had contracted electric power supply are clearly differentiated and favoured [23,21]. In particular, the aim of the RD 2818/1998 was to remunerate more generously those PV systems linked to a consumption centre [24].

[4] According <fn0020>to ASIF, in 2008 the PV sector registered a total investment of 14.500 M€ while the number of employees rose to 41.700.

**Table 1**
Installed cumulative PV power in Spain, 1998–2008. Source: CNE. Source: self-elaboration.

| Installed cumulative power [MW] | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Total power GCPVS | 1.5 | 1.5 | 2.1 | 3.9 | 7.5 | 11.8 | 23.1 | 47.4 | 145.2 | 681.6 | 3,192.5 |
| GCPVS set point; PER 2005–2010 | – | – | – | – | – | – | 37.0 | 52.0 | 77.0 | 121.0 | 190.0 |
| Deviation with respect to PER 2005–2010 | – | – | – | – | – | – | −13.9 | −4.6 | 68.2 | 560.6 | 3,002.5 |
| Total installed power (SR) | 6,259.0 | 7,785.1 | 9,250.2 | 11,235.4 | 13,336.9 | 14,934.8 | 17,506.0 | 19,276.9 | 21,563.2 | 24,715.1 | 28,151.0 |
| Share of GCPVS installed cumulative power in the SR total (%) | 0.02 | 0.02 | 0.02 | 0.03 | 0.06 | 0.08 | 0.1 | 0.2 | 0.7 | 2.8 | 11.3 |

**Table 2**
GCPVS power energy sales in Spain, 1998–2010. Source: CNE and PER 2005–2010. Source: self-elaboration.

| PV sales [GWh] | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Power requirement at power station bus bar | 172.963 | 184.372 | 194.904 | 205.485 | 211.450 | 225.851 | 236.000 | 246.183 | 253.446 | 261.273 | 263.530 |
| SR sales | 20,437.0 | 25,131.4 | 27,507.3 | 31,243.9 | 36,200.0 | 42,145.6 | 46,908.8 | 51,686.2 | 51,971.6 | 57,861.0 | 66,225.9 |
| GCPVS sales | 1.2 | 1.4 | 1.3 | 1.7 | 4.7 | 9.4 | 18.5 | 41.1 | 106.5 | 492.6 | 2,320.0 |
| PER 2005–2010: GCPVS targets | – | – | – | – | – | – | – | 24.5 | 58.1 | 119.3 | 221.7 |
| GCPVS sales in relation to power station bus bar demand | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.2% | 0.9% |
| GCPVS sales in relation to SR's | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.2 | 0.9% | 3.5% |
| Effectively worked hours (SR) | 3,265.2 | 3,228.2 | 2,973.7 | 2,780.8 | 2,714.3 | 2,822.0 | 2,679.6 | 2,681.3 | 2,410.2 | 2,341.1 | 2,352.5 |
| GCPVS effectively worked hours | 803.1 | 885.4 | 613.6 | 434.7 | 634.6 | 796.9 | 799.4 | 866.4 | 733.8 | 722.7 | 726.7 |
| PER 2005–2010: GCPVS effectively worked hours | – | – | – | – | – | – | – | 470.6 | 754.4 | 986.0 | 1,167.0 |

**Table 3**
Annual costs of GCPVS in Spain, 1998–2010 (*In M€*). Source: CNE and PER 2005–2010. Source: self-elaboration.

| Regulated activity costs | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| SR cost | 1,245.2 | 1,476.1 | 1,647.9 | 1,965.3 | 2,355.6 | 2,315.7 | 2,574.8 | 2,718.7 | 2,504.6 | 2,925.0 | 4,006.8 |
| GCPVS cost | 0.1 | 0.3 | 0.3 | 0.4 | 1.4 | 2.9 | 6.8 | 16.4 | 45.5 | 214.0 | 1,049.9 |
| PER 2005–2010: GCPVS cost | – | – | – | – | – | – | – | 9.4 | 22.7 | 46.6 | 85.0 |
| Increase in GCPVS total costs | – | – | – | – | – | – | – | 7.0 | 22.9 | 167.5 | 964.9 |
| Share of GCPVS costs in the SR total | 0.0 | 0.0 | 0.0 | 0.0 | 0.1% | 0.1% | 0.3% | 0.6% | 1.8% | 7.3% | 26.2% |

fewer than 812 kt of $CO_2$ in 2008, which is four times the PER 2010 target of $CO_2$ avoided emissions (see Tables 7 and 8).

Regarding the second objective of the PV energy policy, the Special Regime Power Plants Register (RIPRE) data[5] (sorted according to Table 8) shows that by the end of October 2008 not only the installed cumulative PV power had exceeded by five times the value of the target, but also that the promotion of GCPVS on roof had failed. The RIPRE data also shows that 76.8% of the installed power corresponds to solar parks (Tables 9 and 10). However, this percentage drops to 61.4% when the number of registered PV systems belonging to solar parks is taken into account.

According to the definition of solar parks[6] [24] the previous ratios may also include GCPVS on roofs. To begin with, it is important to note that the way the data of the RIPRE is structured makes it difficult to know whether the facilities are located on the floor or on the roof. Notwithstanding, the data elaborated in this work should be considered conservative, since the sector itself (ASIF[7]) admits that over 90% of the installed power corresponds to GCPVS located on floor. This is in accordance with the fact that the

[5] http://www.mityc.es/Electricidad/Seccion/ProductoresEspecial/Estructura/. <fn0025>October 2008. The way the RIPRE data of October 2008 is structured allows a better study according to the system typology. However, some discrepancies may exist with the data of the CNE reports (see for instance Table 1).

[6] A solar park is the result of the grouping, on the same site, of different PV systems which belong to different holders and share the same evacuation line. Along these 10 years the power of these PV systems, or power units, has varied depending on the power limit set for the most favorable stretch of the economic framework. While as enforced by RD 2818/1998 solar parks were made up of PV systems whose power was equal to 5 kW, in the successive reforms this maximum was raised to 100 kW.

[7] Personal <fn0035>communication.

**Table 4**
Investment in GCPVS in Spain, 2004–2008. Source: CNE and PER 2005–2010. Source: self-elaboration.

| Investment | 2004 | 2005 | 2006 | 2007 | 2008 |
|---|---|---|---|---|---|
| Investment ratio [€/kW][a] | 6,903.0 | 6,903.0 | 6,558.3 | 6,230.3 | 5,198.7 |
| Installed power (PER 2005–2010) [MW] | 11.4 | 15.0 | 25.0 | 44.0 | 69.0 |
| Total installed power [MW] | 11.3 | 24.3 | 97.8 | 536.4 | 2,510.8 |
| Investment (PER 2005–2010) [M€] | 783.5 | 1,035.5 | 1,639.6 | 2,741.3 | 3,587.1 |
| Actual investment [M€] | 783.5 | 1,678.8 | 6,410.8 | 33,421.5 | 13,053.0 |

[a] Source: PER 2005–2010.

**Table 5**
Generation of employment by GCPVS in Spain, 1998–2008. Source: CNE and PER 2005–2010. Source: self-elaboration.

| Employment generation | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Employment ratio (construction and installation) [No. employees/MW][a] | 82.2 | 82.2 | 82.2 | 82.2 | 82.2 | 82.2 | 82.2 | 82.2 | 82.2 | 82.2 | 82.2 |
| Employment ratio (PVS operations and maintenance) [No. employees/MW][a] | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
| Construction (PER 2005–2010) | – | – | – | – | – | – | 933.0 | 1,233.0 | 2,055.0 | 3,616.8 | 5,671.8 |
| Exploitation (PER 2005–2010) | – | – | – | – | – | – | 14.8 | 20.8 | 30.8 | 48.4 | 76 |
| Construction (Total) | 122.3 | 3.5 | 44.3 | 150.7 | 293.2 | 353.4 | 932.9 | 1,999.1 | 8,035.2 | 44,095.0 | 206,390.1 |
| Exploitation (Total) | 0.6 | 0.6 | 0.8 | 1.6 | 3.0 | 4.7 | 9.2 | 19.0 | 58.1 | 272.7 | 1,277.0 |

[a] Source: PER 2005–2010.

**Table 6**
Avoided emissions of $SO_2$ and $NO_x$ by grid-connected PV systems in Spain, 1998–2008 (*In tons*). Source: CNE. self-elaboration.

| Type of power plant | $SO_2$ g/kWh | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CC.TT. H + A | 6.8 | 8.1 | 9.2 | 8.6 | 11.5 | 32.2 | 63.8 | 125.7 | 279.5 | 724.5 | 3,349.9 | 15,775.7 | 20,388.7 |
| CC.TT. LN | 21.8 | 26.1 | 29.6 | 27.7 | 37.0 | 103.4 | 204.5 | 402.9 | 896.0 | 2,322.5 | 10,739.3 | 50,575.1 | 65,363.9 |
| CC.TT. LP | 26.8 | 32.0 | 36.3 | 34.1 | 45.5 | 127.1 | 251.4 | 495.3 | 1,101.5 | 2,855.2 | 13,202.5 | 62,174.9 | 80,355.7 |
| CC.TT. CI | 3.3 | 3.9 | 4.5 | 4.2 | 5.6 | 15.6 | 31.0 | 61.0 | 135.6 | 351.6 | 1,625.7 | 7,655.9 | 9,894.5 |
| CC.TT. FG | 2.2 | 2.6 | 3.0 | 2.8 | 3.7 | 10.4 | 20.6 | 40.7 | 90.4 | 234.4 | 1,083.8 | 5,103.9 | 6,596.4 |
| Total combined cycles | 0.007 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.3 | 0.7 | 3.4 | 16.2 | 21.0 |
| **Type of power plant** | **NO*x* g/kWh** | **1998** | **1999** | **2000** | **2001** | **2002** | **2003** | **2004** | **2005** | **2006** | **2007** | **2008** | **Total** |
| CC.TT. H + A | 3.9 | 4.7 | 5.3 | 5.0 | 6.6 | 18.5 | 36.6 | 72.1 | 160.3 | 415.5 | 1,921.3 | 9,047.8 | 11,693.5 |
| CC.TT. LN | 4.7 | 5.6 | 6.4 | 6.0 | 8.0 | 22.3 | 44.1 | 86.9 | 193.2 | 500.7 | 2,315.4 | 10,903.8 | 14,092.2 |
| CC.TT. LP | 1.8 | 2.2 | 2.4 | 2.3 | 3.1 | 8.5 | 16.9 | 33.3 | 74.0 | 191.8 | 886.7 | 4,175.9 | 5,397.0 |
| CC.TT. CI | 2.1 | 2.5 | 2.8 | 2.7 | 3.6 | 10.0 | 19.7 | 38.8 | 86.3 | 223.7 | 1,034.5 | 4,871.9 | 6,296.5 |
| CC.TT. FG | 1.2 | 1.4 | 1.6 | 1.5 | 2.0 | 5.7 | 11.3 | 22.2 | 49.3 | 127.8 | 591.2 | 2,783.9 | 3,598.0 |
| Total combined cycles | 1.2 | 1.4 | 1.6 | 1.5 | 2.0 | 5.7 | 11.3 | 22.2 | 49.3 | 127.8 | 591.2 | 2,783.9 | 3,598.0 |

CC.TT: coal-fired power station; H + A: coal and anthracite; LN: black lignite; LP: brown lignite; CI: imported carbon; FG: fuel-gas.

**Table 7**
Avoided emissions of $CO_2$ and particles by grid-connected PV systems in Spain, 1998–2008 ($CO_2$ *in kilotons; Particles in tons*). Source: CNE. self-elaboration.

| Type of power plant | $CO_2$ g/kWh | 1998 | 1999 | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CC.TT. H + A | 929 | 1.1 | 1.3 | 1.2 | 1.6 | 4.4 | 8.7 | 17.2 | 38.2 | 99.0 | 457.7 | 2,155.2 | 2,785.5 |
| CC.TT. LN | 949 | 1.1 | 1.3 | 1.2 | 1.6 | 4.5 | 8.9 | 17.5 | 39.0 | 101.1 | 467.5 | 2,201.6 | 2,845.4 |
| CC.TT. LP | 1.012 | 1.2 | 1.4 | 1.3 | 1.7 | 4.8 | 9.5 | 18.7 | 41.6 | 107.8 | 498.5 | 2,347.8 | 3,034.3 |
| CC.TT. CI | 855 | 1.0 | 1.2 | 1.1 | 1.5 | 4.1 | 8.0 | 15.8 | 35.1 | 91.1 | 421.2 | 1,983.6 | 2,563.6 |
| CC.TT. FG | 771 | 0.9 | 1.0 | 1.0 | 1.3 | 3.7 | 7.2 | 14.2 | 31.7 | 82.1 | 379.8 | 1,788.7 | 2,311.7 |
| Total combined cycles | 350 | 0.4 | 0.5 | 0.4 | 0.6 | 1.7 | 3.3 | 6.5 | 14.4 | 37.3 | 172.4 | 812.0 | 1,049.4 |
| **Type of power plant** | **Particles g/kWh** | **1998** | **1999** | **2000** | **2001** | **2002** | **2003** | **2004** | **2005** | **2006** | **2007** | **2008** | **Total** |
| CC.TT. H + A | 0.4 | 0.5 | 0.5 | 0.5 | 0.7 | 1.9 | 3.8 | 7.4 | 16.4 | 42.6 | 197.1 | 928.0 | 1,199.3 |
| CC.TT. LN | 0.4 | 0.5 | 0.5 | 0.5 | 0.7 | 1.9 | 3.8 | 7.4 | 16.4 | 42.6 | 197.1 | 928.0 | 1,199.3 |
| CC.TT. LP | 0.3 | 0.4 | 0.4 | 0.4 | 0.5 | 1.4 | 2.8 | 5.5 | 12.3 | 32.0 | 147.8 | 696.0 | 899.5 |
| CC.TT. CI | 0.2 | 0.2 | 0.3 | 0.3 | 0.3 | 0.9 | 1.9 | 3.7 | 8.2 | 21.3 | 98.5 | 464.0 | 599.7 |
| CC.TT. FG | 0.1 | 0.1 | 0.1 | 0.1 | 0.2 | 0.5 | 0.9 | 1.8 | 4.1 | 10.7 | 49.3 | 232.0 | 299.8 |
| Total combines cycles | 0.02 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.2 | 0.4 | 0.8 | 2.1 | 9.9 | 46.4 | 60.0 |

CC.TT: coal-fired power station; H + A: coal and anthracite; LN: black lignite; LP: brown lignite; CI: imported carbon; FG: fuel-gas.

**Table 8**
Analysis of the RIPRE's data. Classification criteria for grid-connected PVS registered in the RIPRE. Source: self-elaboration.

| Installation type | Classification criteria |
|---|---|
| Solar park | Set of GCPVS (minimum of 2) with consecutive registration number or name belonging to the same central registry |
| Public funded | GCPVS in public buildings and subsidiaries of any public administration, at national, regional or local level. |
| On roof | GCPVS with power of less than 25 kW and registration name belonging to a person |
| Individuals | GCPVS with registration name of a physical person or groupof persons, with a rated power exceeding 25 kW |
| In companies | PV systems with business or cooperative name registration, regardless of the rated power and not classifiable in the above groups |

**Table 9**
Installed cumulative PV power, number of PV systems and installed solar parks in Spain in October 2008. Source: RIPRE. self-elaboration.

| Spain | Total PV systems | | Solar parks | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | No. of installations | Power (MW) | No. of parks | Power of parks (MW) | Total no. of installations in the Parks | $P \leq 5$ [kW] No. of installations | $5 < P \leq 20$ [kW] No. of installations | $20 < P \leq 100$ [kW] No. of installations | $P > 100$ [kW] No. of installations | Power share [%] | Installations share [%] |
| Total | 34,125 | 1,840.6 | 445 | 1,413.2 | 20,951 | 4,320 | 2,448 | 13,865 | 65 | 76.8 | 61.4 |

**Table 10**
Installed cumulative PV power and number of PV systems in Spain according to its typology in October 2008. Source: RIPRE. self-elaboration.

| Spain | Public funded | | | | In companies | | | | Residential and individuals | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | No. of installations | Total power [MW] | Power share [%] | Installations share [%] | No. of installations | Total power [MW] | Power share [%] | Installations share [%] | No. of installations | Total power [MW] | Power share [%] | Installations share [%] |
| Total | 947 | 9.9 | 0.5 | 2.8 | 6,967 | 339.2 | 18.4 | 20.4 | 5,260 | 78.3 | 4.3 | 15.4 |

**Table 11**
The main axes of the legal framework of PVS and its control analogies for the period 1998–2008. Source: self-elaboration.

| Control element | Grid access | Administrative procedure | Economic regime |
|---|---|---|---|
| Foundations | (1) Right of access subject to compliance with the criteria set by Law | (1) The right of the generation business is a pre-existing right subject to the criteria established by Law. | Remuneration based on: (1) Profitability of technology |
| | (2) Access criteria established by Law | (2) Police control established by the Administrative procedure through a set of requirements, procedures and times. | (2) The "distributed" nature of the generated electricity |
| | (3) Established procedures and times | | |
| Objectives | (1) Ensure access and exclude discretionality | (1) Ensure freedom of the power generation activity | (1) Ensure the profitability of the activity of power generation |
| | (2) Restrict the actions of blockade by the distributors<br>(3) Regulatory body ensuring access | (2) Exclude discretionality in the accreditation criteria for the generation activity | (2) Encourage the implementation of PV systems |
| Conditions | Existence of capacity on the grid | Fulfilment of energy, environmental and territorial planning established by Law | Compliance with the criteria established in the SR |
| Control action | (1) Control switch (open or closed)<br>(2) Allow access once checked the control conditions | (1) Control switch (open or closed)<br>(2) Allow this activity once verified the control conditions | (1) Control block<br>(2) Phasing out the error between the set point and the output is suposed |
| Predominant feature | Lags | Lags | *Kp* Proportionality factor: investment incentive |

regions with the lowest population densities accumulate most of the total installed power.

Finally, it is worthy to note that the second target of the PV economic policy not only has not been met but also that, by taking advantage of legal loopholes, other typologies of GCPVS have benefited from the propitious remuneration framework originally intended to encourage GCPVS on roof. This fact together with the consequences it unleashed will be further developed in Section 4.

### 2.2. Analysis of the control applied to the PV energy sector in Spain

In general, when a set point is applied to a physical system in order to obtain a desired result, and provided there is no feedback action of the evolution of the process (i.e. open loop system), it is highly probable that this system will not achieve its objective. Moreover, in some cases, its response can even become unstable. Otherwise, in a system containing a feedback action (i.e. closed-loop system), once a control structure is applied, there are more

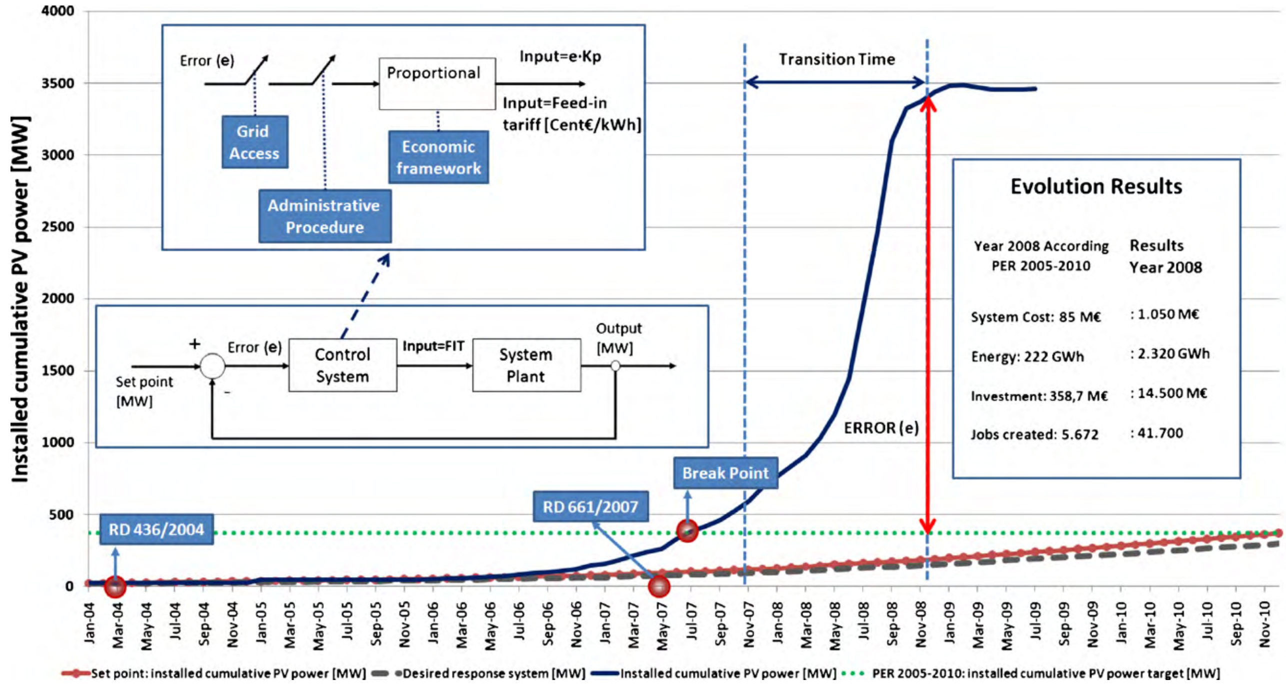


**Fig. 1.** Control system and evolution of the installed cumulative PV power, 2004–2008. Source: self-elaboration.

chances that the process evolution will get closer to the desired response and that the system's stability will be guaranteed.

Diverse elements of the electricity sector laws and the various royal decrees that have regulated the SR (such as the economic framework, the grid access and the "police" administrative procedure) exhibit a behaviour that may be assimilated to that of the typical blocks of basic control theory (see Table 11). Therefore, in order to control the implementation of GCPVS, the simplest closed-loop control structure could be employed (see Fig. 1). This structure would consist of the followings elements:

- The set point, or the desired installed cumulative PV power to be achieved.
- The output, or system response, being in this case the actually installed cumulative PV power.[8]
- The error signal, or the difference between the set point and the actual system's response.
- The control block, or the several energy plans and laws enacted in order to reach the desired power targets.
- The plant to be controlled, or the Spanish PV energy sector.

Therefore, the main objective of this section will be to show those elements of the legal framework that, if applied to the PV sector, will be more likely to cause an unstable response of the system. To achieve this objective some elements of basic control theory will be applied [25,26]. However, it should be noticed that the central issue of this paper is not to precisely model the behaviour of the PV sector but to elucidate the factors that have contributed to its instability.[9] To do so, the following assumptions were made:

- The closed-loop control scheme of the plant is the one described in Fig. 1. The applied set point will be a ramp, because this function represents properly the target of installed cumulative PV power established by the regulator.
- The transfer function of the system plant, $G(s)$, is considered as linear, time invariant and stable.[10] In addition, physical assembly time of PV systems is considered as an inherent part of the system time constant.
- The control block, whose output is the FIT value, acts as a proportional gain ($Kp$), whose value is modified by the different legislative actions that have been enforced.

Once these criteria had been established, the effects on the system output of the different elements of the control scheme were evaluated. This was made by considering three different cases of increasing complexity:

- First case: the control structure was reduced to a pure economic control action which is firstly modelled by a proportional gain $Kp$ block.
- Second case: the possible disturbances due to the transition mechanism stipulated in RD 661/2007 were modelled as an added set point superimposed to the initial one of a ramp type.
- Third case: the grid and the "police" control, which are both modelled by a delay block, were added to the simple control structure of the first case.

In the closed-loop control scheme, the system output can be related to the applied set point by means of a complex-variable mathematical function, which is called closed-loop transfer function (1). In this equation, "$s$" is the name of the independent complex-variable, $C(s)$ and $R(s)$ stand for the system output and the applied set point respectively, and $G(s)$ is the transfer function of the plant. A necessary and sufficient condition for the stability of the system output is that the real part of all the closed-loop transfer

[8] As mentioned in Section 2.1, besides the first target of attaining a determined installed cumulative PV power there exists a second target of promotion of PV systems on roof. Unfortunately, the way in which the official statistics are displayed makes impossible to exactly discern which portion of the total installed power corresponds to facilities located on roof.

[9] It should be emphasized that since a mathematical model for the real PV Spanish sector was not deployed, its suggested stability is only an initial assumption. Nonetheless, it must be pointed out that there's no physical evidence that this sector – or any other one similar to it – are intrinsically unstable. So said, it seems reasonable to take the stability of the sector as a valid hypothesis.

[10] The analyzed system is ideally considered to be as a single-input single-output one. Its stability is guaranteed because its root locus is assumed to be located in the left half-plane of the complex-variable "$s$" domain.

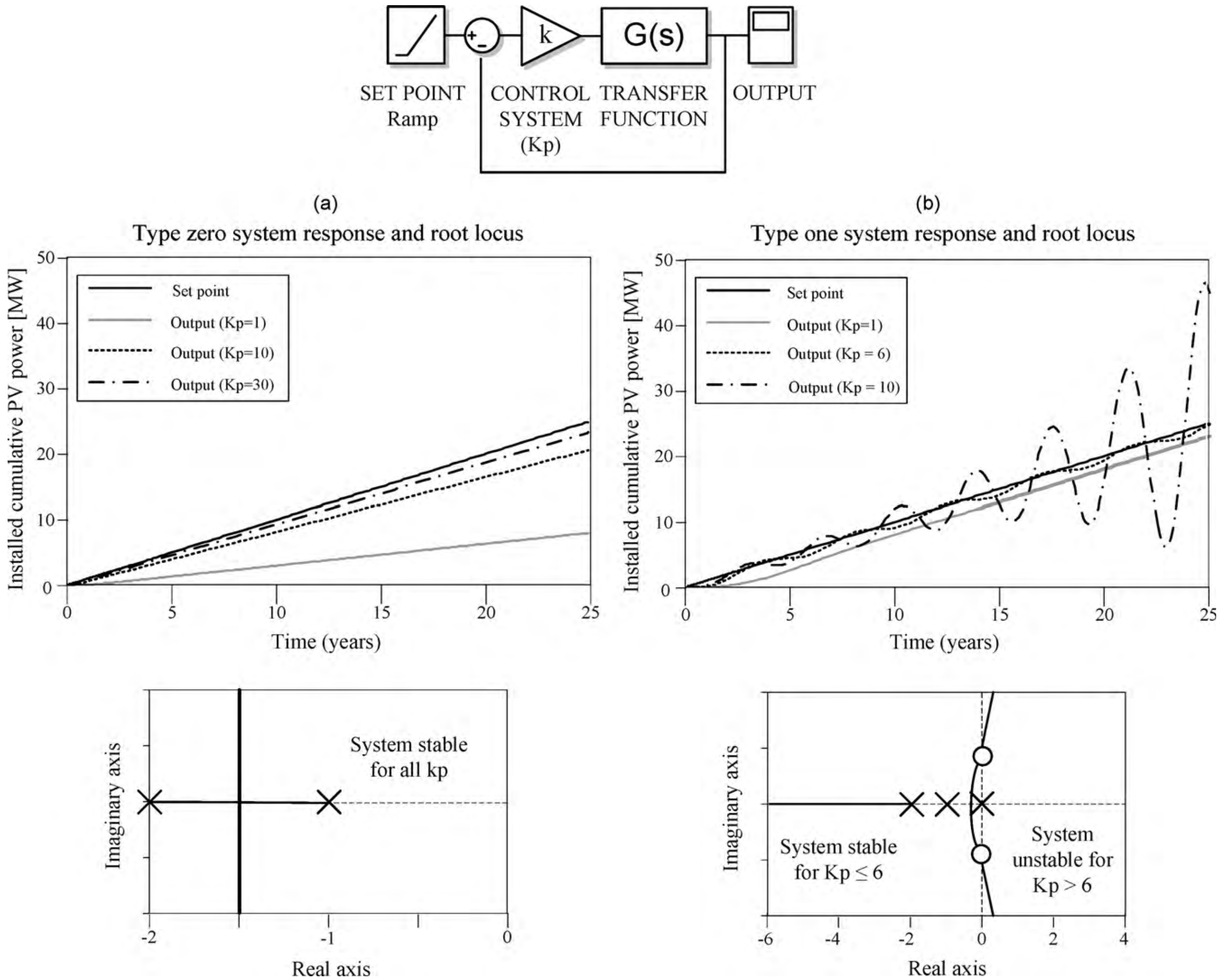


**Fig. 2.** Type zero and type one system response and root locus. Source: self-elaboration.

function poles are located in the left half-plane of the "*s*" complex-variable domain. The closed-loop poles are the roots of the polynomial in the denominator of the closed-loop transfer function, which is also known as the characteristic equation (2). Note that the locus of the closed-loop poles is dependent on the value of the gain *Kp*. Thus, for certain values of the gain *Kp* in the control block, the system output could turn unstable.

$$\frac{C(s)}{R(s)} = \frac{Kp \cdot G(s)}{1 + Kp \cdot G(s)} \tag{1}$$

$$1 + Kp \cdot G(s) = 0 \tag{2}$$

Fig. 2a illustrates the effects of the *Kp* gain value in the stability of the system when a ramp type set point is applied to a zero type[11] transfer function $G(s)$, i.e. a transfer function without null poles. It also shows that even with higher gain *Kp* values the system remains stable.[12] However, if a null pole is introduced in the transfer function $G(s)$, thus becoming of type 1, the stability of the system is altered (Fig. 2b). In this case, for progressively increasing values of the gain *Kp*, the closed-loop poles become closer to the right half-plane of the complex domain and so too closer to the instability. Moreover, once a critical value of the gain *Kp* is surpassed, the system response turns unstable.

As illustrated, for certain types of systems the value of the gain *Kp* can cause an unstable output, or, what is the same, the applied FIT values to the Spanish PV sector could be the responsible for its oversized response. This fact corresponds to the first of the aforementioned cases and will be analyzed in depth in Section 3.1.

Nevertheless, the key point to be elucidated is whether the instability of the system is caused only by the value of the control gain *Kp* or other elements need to be taken into account to fully understand such instability (Fig. 3).

The monthly installed power evolution from May 2007 to October 2008 (see Fig. 4) shows that not only the FIT value influenced the instability of the system, but also that there was a disturbance introduced in the control scheme due to the transition mechanism stipulated in the RD 661/2007.[13] This mechanism provoked a high level of uncertainty in the Spanish PV sector, acting as a "call for inversion". It can be represented as a pulse added unintentionally to the system's set point as well as held responsible for its out-of-scale response. This situation corresponds to the second case and will be further developed in Section 3.2.

Finally, in the third case under study, the access to the network and the administrative procedure are modelled as an equivalent

[11] The "type" of a transfer function is its number of null poles.

[12] A system is stable if a bounded input produces a bounded output.

[13] RD 661/2007 stipulated that, once accumulated PV power reached the 85% of the target, there would be a transition period of one year to join to the economic framework established therein.

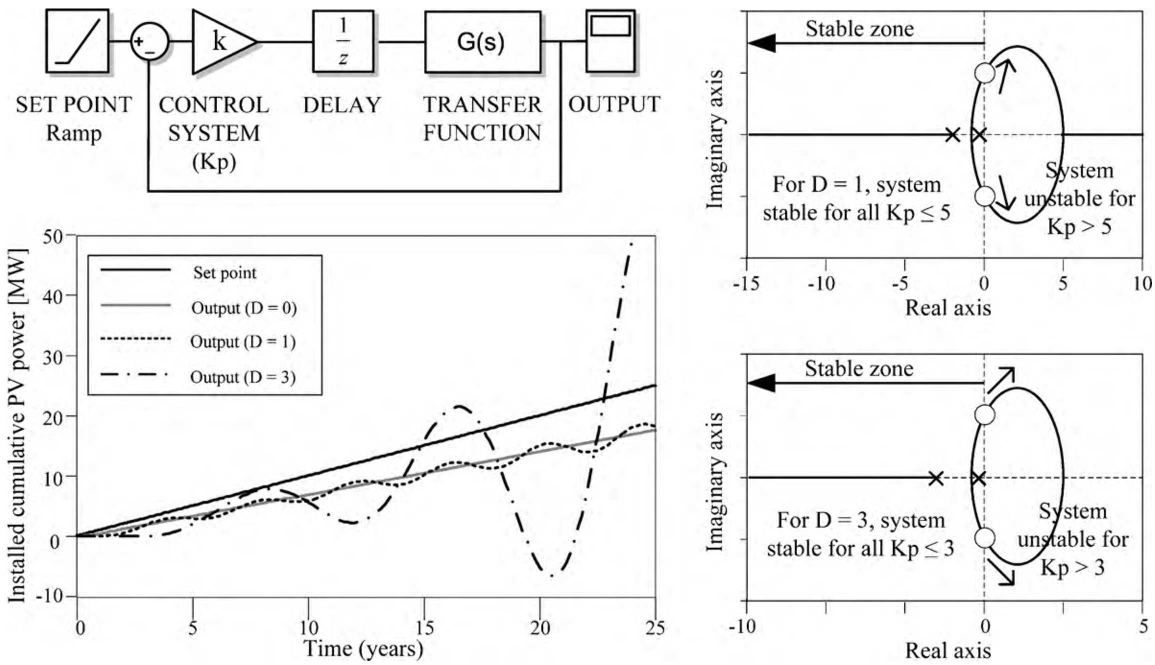


**Fig. 3.** Type zero system response and stability for different delays in years. Source: self-elaboration.

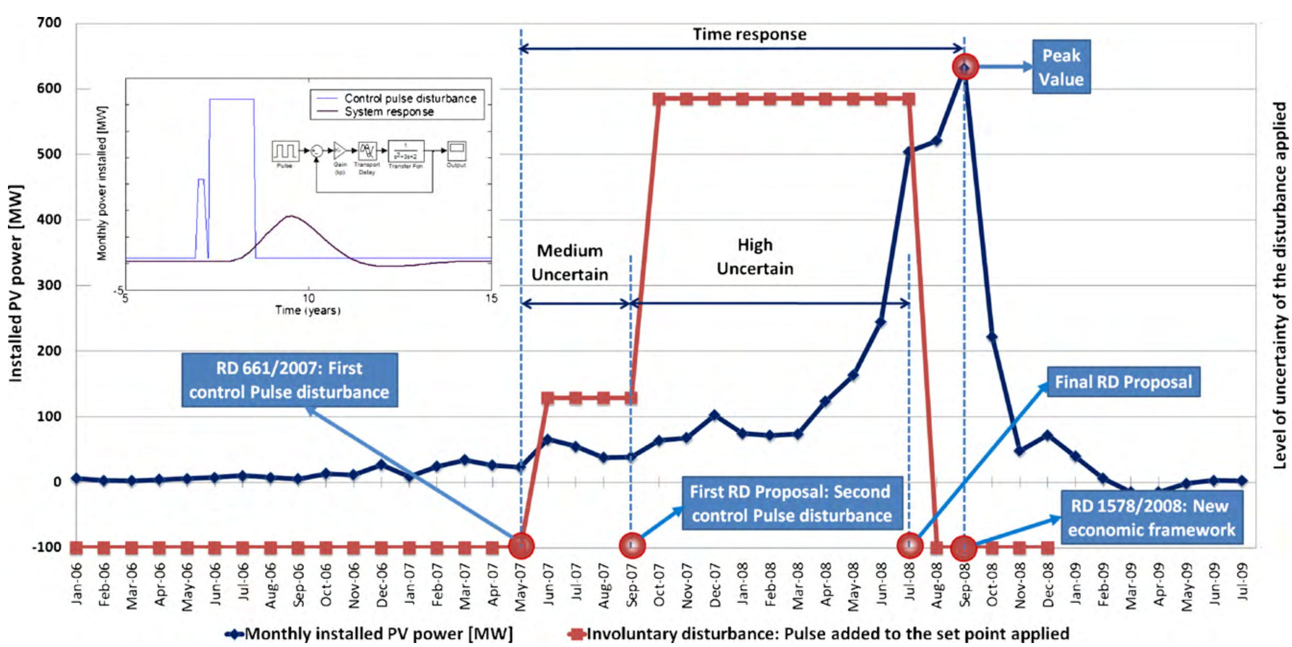


**Fig. 4.** Analogy between system responses and a control pulse set point. Monthly installed PV power from May 2007 to October 2008. Source: self-elaboration.

delay. Fig. 3 shows that, although the control gain *Kp* was not able to unsettling the type zero system in Fig. 2a, the already introduced delays cause the output of the system to become unstable. Definitely, as the delay (*D*) increases the output of the system becomes more unstable. Likewise, Fig. 3 reveals that highly delayed systems present higher sensitivity to the value of the control *Kp*. This destabilizing effect of the delays will be analyzed in detail in Section 3.3.

The evolution of the closed-loop system output is influenced by several factors, such as the implemented control action, the possible disturbances and the existing delays. Thus, the analogy established between the simple closed-loop control scheme (Fig. 1) and the arrangement of the Spanish PV sector will be the tool used to analyze in depth how the aforementioned factors might have hindered the achievement of the targets set by the PV economic policy.

## 3. Control structure analysis

### *3.1. Control algorithm: feedback and FIT value in the "power boom"*

The first control model for the PV sector to be analyzed was a proportional action (Section 2.2), i.e. the FIT applied to encourage the attainment of the desired objectives was proportional to the error, or the difference between the set point and the instantaneous degree of accomplishment of the objectives. In this simple

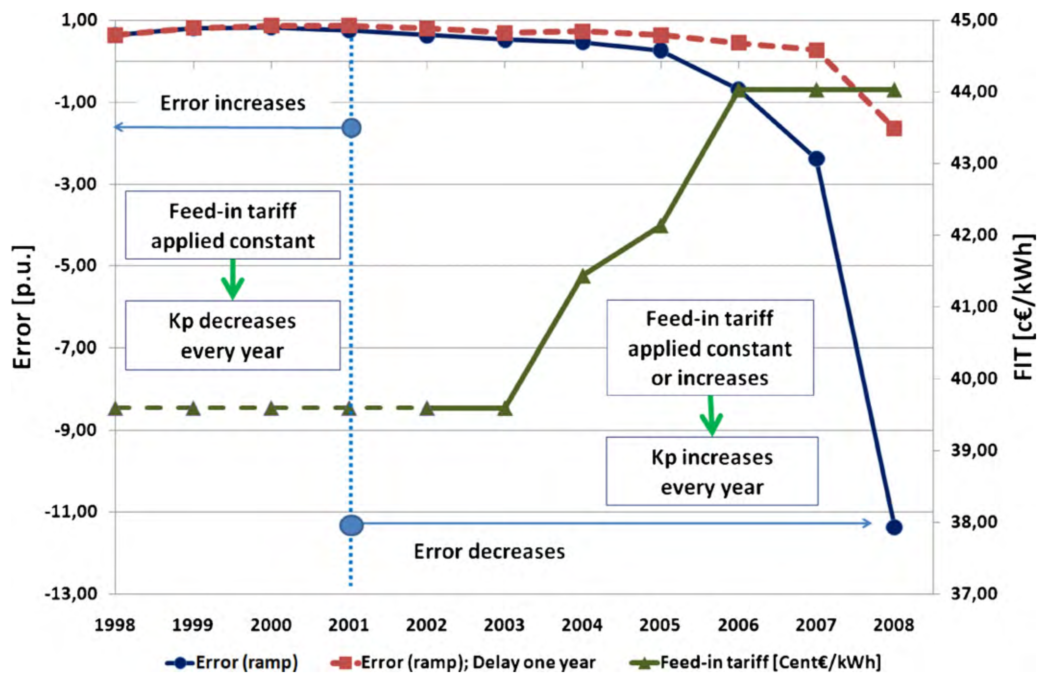


**Fig. 5.** Real evolution of the input or feed-in tariff, 1998–2008. Source: self-elaboration.

**Table 12**
The economic control: the applied set point and the proportional control action, 1998–2008. Source: self-elaboration.

| | RD 2818/1998: 1998–2004 | RD 436/2004: 2004–2007 | RD 661/2007: 2007–2008 |
|---|---|---|---|
| Set point | $P<5$ kW: 50 MW<br>$P>5$ kW: undefined | 150 MW undefined power step | 371 MW undefined power step |
| Power step | $P<5$ kW<br>Case (A): fixed premium<br>$R=P_m+P_r\pm ER$<br>*R*: *Retribution*<br>$P_m$: average market price<br>$P_r$: Premium of 0.360607 €/kWh<br>*ER*: Completion of reactive power<br>Case (B): fixed feed-in tariff<br>$R=0.396668$ €/kWh | $P\leq 100$ kW<br><br>Case: regulated tariff<br>$R=575\%^*$ AET (first 25 years) [cent€/kW h]<br>$R=460\%^*$ AET (after the first 25 years) [cent€/kW h] | $P\leq 100$ kW<br><br>Case: regulated tariff<br>$R=44.0381$ [cent€/kW h] (first 25 years)<br>$R=35.2305$ [cent€/kW h] (after the first 25 years) |
| | $P>5$ kW<br>Case (A): fixed premium<br>$R=P_m+P_r\pm ER$<br>$P_r$: premium of 0.180304 €/kWh<br>Case (B): fixed feed-in tariff<br>$R=0.216664$ €/kWh | $P>100$ kW<br>Case (A): regulated tariff<br>$R=300\%^*$ AET (first 25 years) [cent€/kW h]<br>$R=240\%^*$ AET (after the first 25 years) [cent€/kW h]<br>Case (B): sale to electricity market<br>$R=P_m+P_r+1\pm ER$<br>*I: incentive*<br>$P_r=250\%^*$ AET (first 25 years) [cent€/kW h]<br>$Pr=200\%^*$ AET(After the first 25 years) [cent€/kW h]<br>$I=10\%^*$ AET [cent€/kW h] | 100 kW $<P\leq 10$ MW<br>Case: regulated tariff<br>$R=41.75$ [cent€/kW h] (first 25 years)<br>$R=33.4$ [cent€/kW h] (after the first 25 years) |
| | | | 10 MW $<P\leq 50$ MW<br>Case: regulated tariff<br>$R=22.9764$ [cent€/kW h] (first 25 years)<br>$R=18.3811$ [cent€/kW h] (after the first 25 years) |

kind of control mechanism, the input applied to the plant is expected to decrease along with the system's error.

However, this simple analogy fails to describe the evolution of the FIT values during the period 1998–2008 (Fig. 5). In fact, while the error was increasing (1998–2001), the FIT value remained constant, or what is the same, the resulting proportional gain *Kp* was reduced progressively.[14] But, when the error was diminishing (2002–2008), the proportional gain *Kp* value was increased: first, during the period 2004–2006 because the FIT was tied legally to the average electricity tariff (AET), and later on, during 2006–2008 because the FIT was kept constant. In fact, during the 1998–2008 period, the error of the system was not considered at all by the control structure (see Table 12), which means that the system was transformed into an open loop system.[15]

The reports by CNE and the Ministry of Industry [27,28] show up the existence of an over-incentive in the economic framework applied to the GCPVS, which seems to have been unnoticed or unattended. Also, these reports hold the PV facility promoters responsible for not having translated the progressive reduction of

[14] This was one of the initial barriers which hampered the evolution of PV systems, thus delaying their growth.

[15] The evolution of the installed cumulative PV power deployed in Fig. 1 shows the typical response of an open loop system.

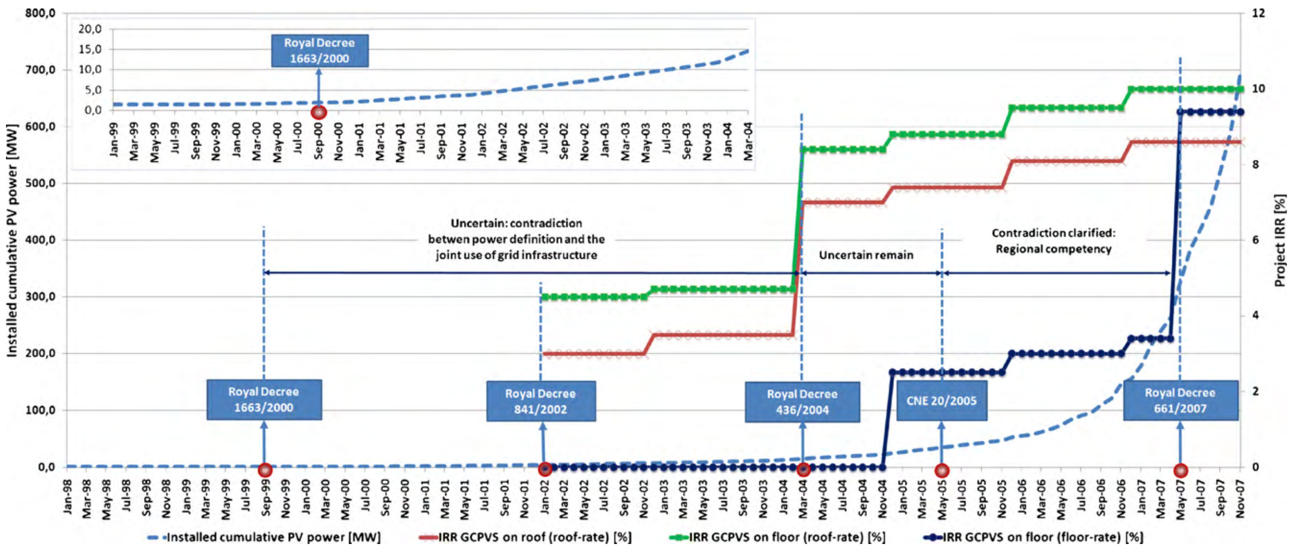


**Fig. 6.** Evolution of the uncertainty between the economic framework and the joint use of grid infrastructure. Source: self-elaboration.

equipment costs to the PV systems' holders, and consequently, to the electricity consumers.

Figs. 5 and 6 illustrate how the Government control actions made GCPVS very profitable, which explains the interest of the investors for this option and the consequent outsized increase of the installed cumulative PV power. By the end of 2007 the economic euphoria was still prevalent in Spain, making it tremendously easy to raise funds for PV projects. Moreover, when the first signs of the real-estate crisis arose, GCPVS rapidly caught the eye of investors due to its rather juicy and guaranteed retribution by law.

At this point it is necessary to remark that:

- The previous facts have been hardly considered in the literature, and the analyses performed have only focused on the consequences of the excessive increase of the PV installed power, but not on the mechanisms behind the problem. Although it is true that the FIT value might have encouraged such GCPVS growth, it is also true that some incorrect control mechanism might have enabled it.
- As previously mentioned, the emphasis on the monetary value of the retribution in detriment of the self-control mechanism could have led to this misdiagnosis. Under this assumption, it is understandable that the FIT value in 2007 had not yet been perceived as a source of disturbances and that, consistently, any potential risk had been discarded [29]. This may explain why the FIT value for the GCPVS experienced no reduction[16] at all (RD 436/2004 and RD 661/2007).

In conclusion, one of the reasons for the outsized installed cumulative PV power was the implemented control action, which in fact did not take into account the degree of accomplishment of the objectives of the economic policy in order to modulate the value of the applied FIT.

### 3.2. Transition mechanism and system response

As previously shown, the control structure and the consequently applied FIT values allow justifying the instability of the system but not to that extent. To duly understand the outstanding behaviour of the PV sector we should ebb to the Spanish economic context. Spain's economic situation in 2007 definitely played a role in the final spectacular development of the PV sector. By the time the first signals of the economic and financial crisis became evident, the PV sector appeared as a safety and profitable refuge for the hefty profits already amassed by the real-estate sector. In fact, PVS high return and ease of funding rapidly converted them in an attractive financial product even for investors from abroad. In this context, the RD 661/2007 was the fuel to this PV bubble growth—e.g. the anecdote goes that the PV sector was dubbed "the bricks No. 2 sector" of that period. It was during this frenzy that many investors, alien to the sector, got a stake in the PV business either as installers or equipment dealers. The latter made in turn that the final price of the equipments remained artificially high, which explains the 50% collapse in PV equipment prices a few months later. Also, the tremendous pressure exerted on the demand for PV equipments determined that the PV power manufacturers had to quickly adapt to respond to the increasingly tight delivery conditions and risk losing market share.

Another significant and decisive factor that contributed to aggravate the evolution of the total power attained by GCPVS (Fig. 7) was the transition mechanism established by the article 22 of RD 661/2007. It stipulated that, once the accumulated PV power reached the 85% of the target, there would be a one-year transition period for those facilities still under construction to be inscribed in the (RIPRE)[17] in order to avail of the generous economic conditions of the RD 661/2007. If the RIPRE registration was not obtained on time, the remuneration would be equivalent to the final hourly electricity production market price (FHEPMP).[18]

This mechanism introduced a lot of uncertainty in the sector, prevented a viable business planning[19] and left the PV industry with the perception that it had no future in Spain. For all this, since

[16] Other authors went further to express the lost opportunity for not having introduced such reduction on time [9].

[17] Every authorised facility must be registered in the Administrative Register of Energy Production Facilities under the Special Regime.

[18] This term is very similar to that of the RD 2818/1998. Notwithstanding, under the RD 2818/1998 the term of reference was not the FHEPMP but the FAHEPMAP, which stands for "final average hourly electricity production market price". The FAHEPMP, as defined by the RD 2818/1998, is the average price that must be paid at each hour by those who acquire energy by buying it on the electricity production market and liquidated by the market operator.

[19] As some recognised professionals of the PV sector explain, the payment established for those facilities legalized after the transition period (FHEPMP) was totally insufficient, rendering the investment unattractive. In only one year, the production cost should be reduced from 6.3 €/Wp to 0.5 €/Wp in order to maintain the same IRR.

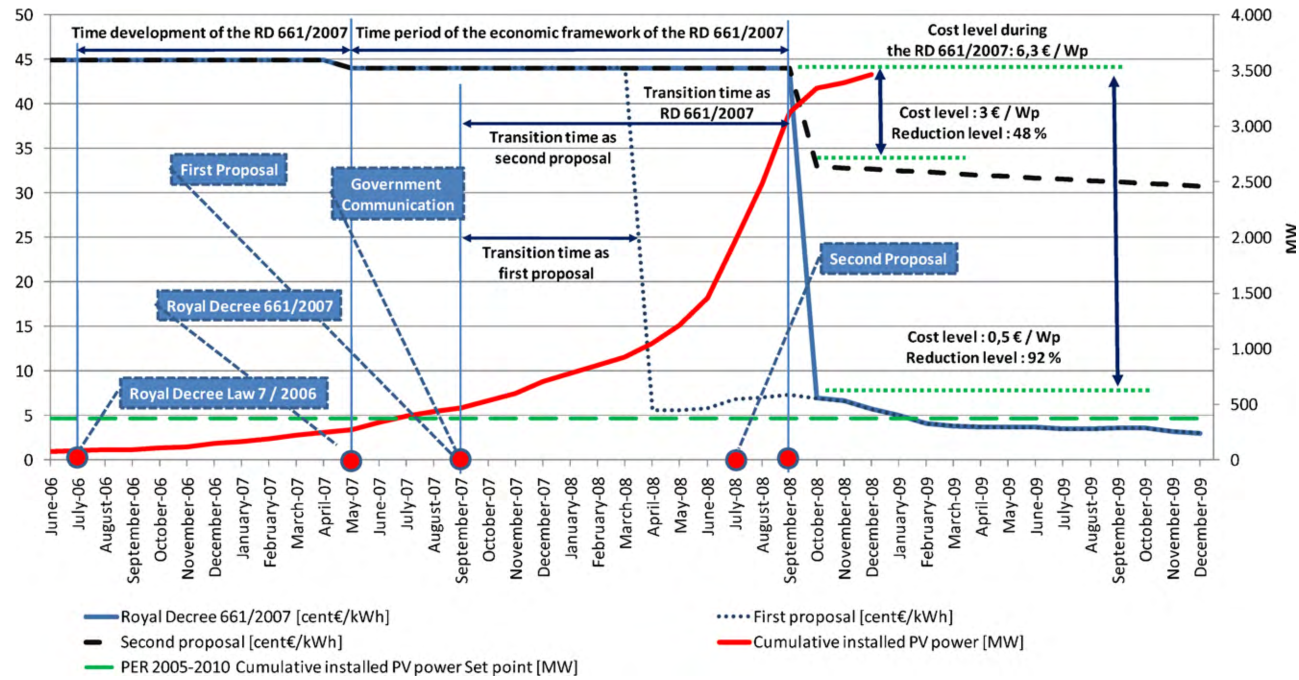


**Fig. 7.** Transient mechanism response. Source: self-elaboration.

the very publication of the RD 661/2007 in May 2007 companies competed to have as many PV facilities fully operative and registered in the RIPRE as possible.

In September 2007 the 85% of the power objective for 2010 was reached (see Fig. 1). Immediately after, the deadline of the transition period was established on September 28th, 2008 [30] and a first proposal of the new economic framework to be applied after the transition period was published [31].

In this first proposal the duration of the new economic framework was not linked to a determined time period but to the achievement of an installed power level of 1200 MW. If the power limit was exceeded during the transition period this would entail its automatic termination. In this case, the retribution for those facilities that have not been duly inscribed at the RIPRE would be the FHEPMP, which rendered the new proposed economic framework absolutely worthless.

Needless to say, the *de facto* retroactivity introduced in the new power level restriction to maintain alive the transition period or to determine the temporal scope of the new economic framework (if ever applied) provoked high uncertainty and immense fear in the PV sector. Moreover, at the very beginning of the transition period it was already probable that the power limit of 1200 MW established in this first proposal would be easily exceeded, which in fact concealed a reduction of the transition time (see Fig. 7). This reason led the CNE to report unfavourably on this first proposal [32].

Only close to the end of the transition time, by July 2008, a second and last proposal was published. The delay in undertaking any corrective measure was another important factor that affected the evolution of the installed cumulative PV power as it introduced even more uncertainty in the PV market [27], thus reinforcing the idea that there was no promising future for the Spanish PV sector. This lack of proactivity might also have amplified the "call for inversion" effect introduced by the RD 661/2007 and the subsequent first proposal.

In essence, the RD 661/2007 was the offshoot of the urgent need for change in the economic framework of the SR, also with respect to the PV sector. By the time the RD 661/2007 came into force (see Fig. 1), the GCPVS were closer to its energy target, which meant the overincentivated FITs initially applied were not yet necessary besides leading to a higher economic burden for the final consumer. Ultimately, the sense of urgency behind the FIT reduction – the control action chosen to adapt the GCPVS to the new economic reality – was to keep the FIT value for one more year after having attained the 85% of the energy target. This mechanism, together with the particular moment of hype of the Spanish economy, might have contributed to offset the RD 661/2007 a priori well intended aims. Moreover, it forced the sector into a hectic dynamics, installing as many PVS as it was capable of, which sooner or later would provoke an avalanche effect in the installed cumulative PV power records. Indeed, the initial lack of definition in its date of entry into force as well as the late introduction of a retroactive mechanism that might have shorten *de facto* the duration of the transition period along with the lack of an adequate and timely regulatory response caused the investors to lower their IRR expectations at the end of the transition time with its devastating effects on the PV market.

This effect corresponds to the second case considered in Section 2.2, where the disturbance related to the ambiguity introduced by the transition period stipulated in the RD 661/2007 was modelled by a superimposed pulse type set point that ultimately contributed to the system unstable response (see Figs. 1 and 7).

### 3.3. The effect of delays

The impact of the several delays inherent to the control structure on the system's behaviour should not be underestimated.

Clearly, one of the most important delays during the period 1998–2008 was motivated by the administrative procedure which acted as a control action to ensure compliance with the regulated targets in the field of electricity generation, whether purely technical (grid access included), environmental or territorial. These control measures, implemented by the different administrations at the local, regional and national levels with jurisdiction over the matter, proved to be highly complex due in part to the large amount of administrative acts and to the diversity of the administrative procedures in Spain.[20] As an example, Fig. 8

[20] A clear understanding of the structure of the administrative procedure is given by del Río and Unruh or Algora [20,33].

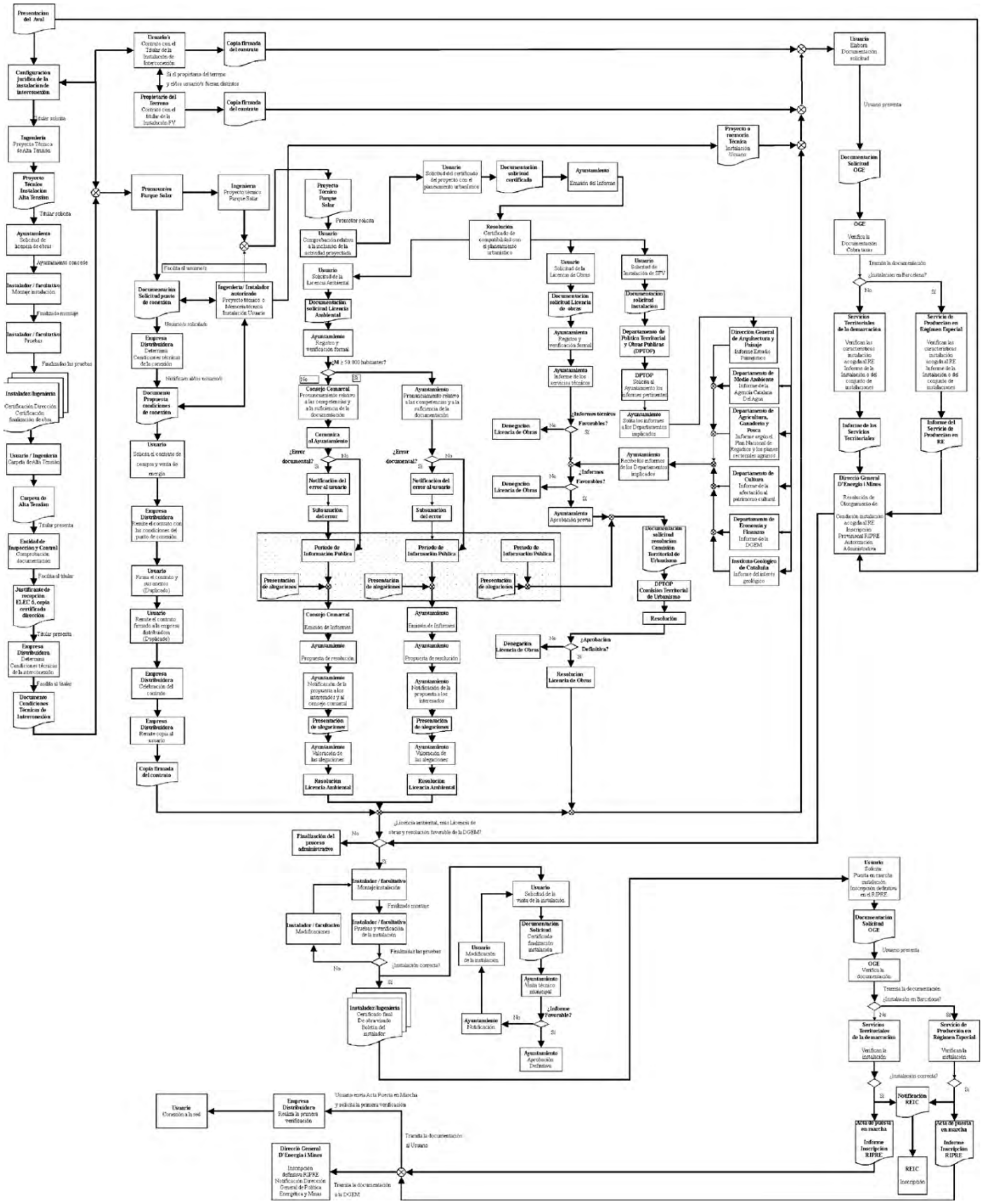

**Fig. 8.** Administrative procedure for PV systems on floor. Catalonian case. Source: self-elaboration.

provides the scheme of the procedure required by a regional administration, whose complete fulfilment may be estimated from 12 to 24 months.

As it will be further explained in Section 4, it is noteworthy how an unexpected effect of the promotion mechanism of the GCPVS on roof could introduce even more complexity into the already entangled administrative procedures. In the period ranging from 1998 to 2005 many doubts arose about how to interpret the Law and, consequently, on how to develop the corresponding administrative procedures. This regulatory uncertainty acted as a delay that held back the growth of the installed cumulative PV power and was fuelled again once the situation was clarified by the CNE (see Fig. 6).

To a lesser extent, the grid access could be considered too as a delay during the analyzed period. It is fair to note that the main constraint on the access of PV systems to the network can be found in the attitude of the utilities and not in the grid access regulation itself. This constraint especially extended to PV systems connected to a high voltage grid,[21] which still lack a specific framework and need a distribution transformer[22] to get access to the network connection.

[21] The RD 1663/2000 has played an important role in ensuring the access of PV facilities to low voltage networks, establishing not only the implementation process and timing, but also setting the technical conditions to carry the process forward.

[22] The RD 1955/2000 (art. 38.2) states that "... the transformer's power plants and its infrastructure are not part of the distribution grid..." This circumstance determined that PV systems connected to high voltage grids have experienced greater generation expenses since the cost of the transformer and the grid infrastructure shall be paid by the holders of the PV system. In some cases, they ought to undertake also the investments regarding grid reinforcement which are clearly discriminatory and restrictive.

During the period 1998–2007, as the PV sector recognizes, the joint control exerted by the grid access regulation and the CNE,[23] has reduced the impact of restrictive practices on the grid access, favouring in turn the implementation of GCPVS. However, the change introduced in the former Law 54/1997 by Law 7/2007, limited the favourable action of the regulatory body on the period 2007–2008.[24]

In conclusion, the delays introduced in the process have contributed to the poor performance of the control action and to the failure in the accomplishment of the system's objectives. These delays prevented the possibility to quickly foresee the real effects of FIT values so as to anticipate any potential dysfunctional behaviour of the PV market. This, in turn, may partially explain the over-incentivised control action—Fig. 5 also shows the importance of the delay in the error's evolution and its consequences in the input of the system. In the analogy established in Section 2.2, this analysis corresponds to the third case of study.

## 4. The special case of on roof GCPVS

### 4.1. The unintended barriers against the GCPVS expansion

There were a great number of barriers which initially prevented GCPVS to spread out in Spain, most of which have already been identified in several studies [34,22,20,11]. Paradoxically, the greatest obstacle for the consistent development of PV systems has been the promotion mechanism designed to encourage the installation[25] of one particular type, the GCPVS on roof.

The reasons for these barriers were, on the one hand, the false univocal relationship assumed between the power of a PV system and its typology (whether located on floor or on roof). On the other hand, there was the inadequate definition of the power of a PV facility and the criteria for the joint use of the distribution transformer by different PV systems. This sort of misconceptions in the legal framework led to a regulatory uncertainty in the administrative procedures enacted by the regional authorities[26] (as told in Section 3.3) that finally resulted in a lack of promotion of PV systems on roof and a delayed growth of the other typologies.

As mentioned in Section 2.1, one of the objectives of the energy policy was the promotion of GCPVS on roof. In order to accomplish so, the economic framework established in the RD 2818/1998 granted a better remuneration to small PV facilities with rated power up to 5 kW on the premise that the PV systems located on roof would be precisely those with lower power ratings. Consequently, since the remuneration was a function of the rated power, the way it was determined or assigned to a PV facility was of key importance.

The first conflicts emerged in the PV systems connected to a high voltage grid, where a distribution transformer was required. The electrotechnical regulations[27] established a limit of 100 kVA for generated power discharged in low voltage grids. Higher generated powers should be evacuated in high voltage grids. Therefore, when high voltage grids were involved, it was assumed that the related PV facilities corresponded to the on-floor type and not to the on roof type.

The RD 2818/1998[28] considered that high voltage GCPVS installed in a same physical location could have either a single holder or several ones (Fig. 9, cases A and B, respectively). PV systems of different holders in a same location should share, whenever possible, the same distribution transformer for the evacuation of electricity.[29]

In the case of a single installation of a unique holder, the power assigned to the PV facility obviously coincided with its rated power. But, in the case of PV systems belonging to different holders, they were automatically considered as a single PV system whose power was the sum of the power of all the PV units discharging their energy to the same distribution transformer. In turn, this total power was taken as the basis for determining the corresponding economic retribution.

However, the RD 2818/1998 also considered a third configuration by which PV units in a same location belonging to different holders could maintain their independency status provided they would not connect directly to the distribution transformer, but through a previous intermediate transformer (Fig. 9, case C). In this case, all the PV systems connected to a particular intermediate transformer were computed as one independent PV facility and its own rated power was taken as the basis for determining the corresponding economic retribution.

The PV sector found in the latter configuration a perfect way out to the low profitability it experienced in the years 1998–2004. In order to take advantage of the most favourable retribution assigned to PV facilities with rated power up 5 kW, the total power of the new high voltage GCPV installations on floor was fragmented into 5 kW modules. The holdership of every module was assigned to a different company, and every module maintained its independence from the others that were connected to the distribution transformer by a previous intermediate one. This gave birth to the so-called "solar farms"[30] or solar parks. Solar farms were the result of grouping a set of small PV systems or power units, located in the same site, with different holdership and with rated power up to 5 kW (see Fig. 9, case D).

### 4.2. The dysfunctional outcomes of an ill-defined policy

The return of PV systems with rated power exceeding 5 kW – supposedly of the on-floor type – (see Fig. 6), was much lower than that obtained by systems up to 5 kW – presumably of the on roof type – because of the different tariffs they enjoyed. It is not surprising then that most of the solar parks consisting of PV systems with rated power of 5 kW belong to this period. This especial focus on solar parks enabled PV companies to acquire the necessary knowledge and skills that would ultimately enable the systematic reduction of the construction and operations times with the corresponding beneficial impact on the competitiveness of the sector due to efficiency gains. Once knowledge is acquired, the construction of this sort of installations is easier relative to those located on roof, whose structural solutions might lead to increased complexity.[31]

This practice, which was defined by the administration as a trick, had two very important effects. First, it allowed PV installations on floor to receive the FIT value that initially was aimed for PV systems on roof. Second, it had a psychological effect on investors. This interpretation of the law allowed small investors to have their *own* PV plant at the cost of participating in a

[23] In this period, 24 grid access conflicts were submitted to the CNE. Nineteen of them were readily estimated and only one was definitely rejected.
[24] None of the nine grid access conflict submitted during this period was solved favourably.
[25] According to the interviewed industry sources, this barrier has been the main impediment for the proper evolution of the installed cumulative PV power. Surprisingly, though, it has been largely ignored in most studies.
[26] Most of the administrative procedures for GCPVS on floor enacted by the Autonomous Communities have been approved after May 2005.
[27] REBT ITC-BT-40.
[28] RD 2818/1998. Article 2. Power definition.
[29] RD 2818/1998. Article 20. Section 5.
[30] A solar energy farm is the name used by the PV industry to define the PV power plants. This name is closely connected with the trade name with which a company used to call its first solar power plant.
[31] This view is shared by all the interviewed companies working in the construction and operation of PV systems.

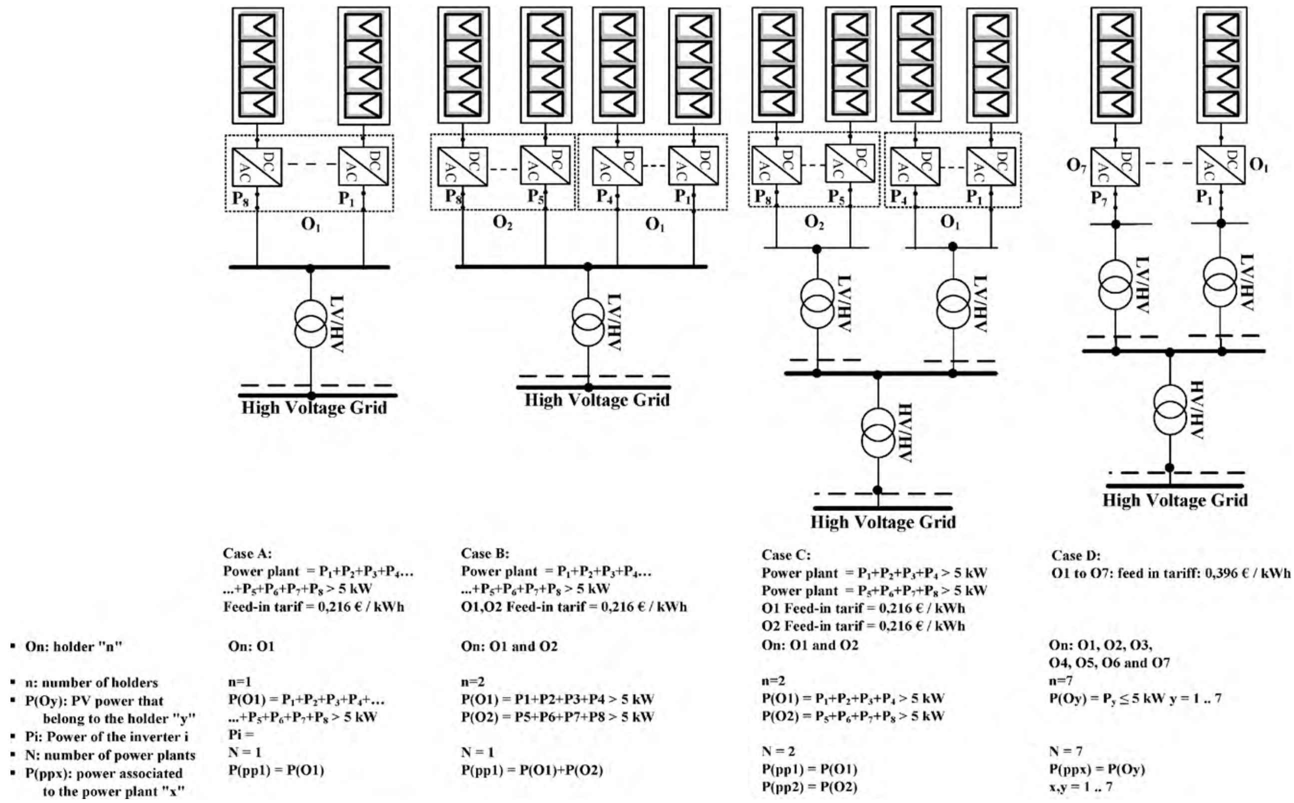


**Fig. 9.** Economic framework and joint use grid infrastructure under the RD 2818/1998. Government's vision and PV sector solution. Source: self-elaboration.

corporation that held the 5 kW PV system.[32] For large investors, this interpretation meant higher economic returns. It was only necessary to create as many different companies as PV systems of 5 kW existed.

Obviously, this situation increased the administrative complexity, since each 5 kW sub-system of the entire plant required a specific authorization procedure. It was also necessary to establish the legal status and ownership of the distribution transformer as well as the allocation of its losses to the different PV systems. As might have been expected, the contradiction engendered between the interpretation of the law and its spirit brought forth great confusion among the different regional administrations in relation to this new practice of the PV sector, up to the extent of generating rejection.

### 4.3. The path to overcoming the controversies: first attempts and close-up

To end with this confusion, the CNE finally issued a clarifying report [24] stating that such atomized PV facilities complied with the law (RD 2818/1998) but not with its spirit, which was to encourage the "in situ" generation and consumption of PV power. Accordingly, the report suggested an urgent change in the law aimed at avoiding unnecessary equipment duplication (Fig. 9, case C), and proposed to increase from 5 to 100 kW the maximum power permitted to benefit from FIT intended for on roof systems.

That increase came into force with the RD 436/2004. However, the confusion arising from the controversial definitions of power[33] and the joint use of the distribution transformer remained: the FIT value was kept in terms of power and not in terms of the typology of the PV facility, and the necessary changes on the way to determine of power of a PV installation were not introduced.

These inconsistencies went on to affect PV systems connected to the high voltage network through a distribution transformer. Indeed, the higher power ratings now related to the most beneficial FIT contributed to intensify even more the magnitude of the controversy because of the bulky profits at stake.

Readily, the CNE remarked on the utter contradictions still prevalent in the RD 436/2004 and dwelled on the legal uncertainty that GCPVS could be exposed to [35]. For instance, for a single GCPVS on floor, connected to a high voltage grid, yielding no more than 100 kW (Fig. 10, case A, RD 436/2004), the FIT value would be 575% higher than the average electricity tariff (AET). However, the economic framework of this installation could happen to be suddenly altered. According to the third provisional transition, if the holder of an adjacent plot would like to connect a PVS to the grid, he ought to do so, wherever possible, from the extant grid infrastructure. In this case the FIT value for the two GCPVS, belonging to different holders and individually yielding no more than 100 kW but jointly exceeding the 100 kW threshold (Fig. 10, case B, RD 436/2004), could drop to only 300% above the AET as both PV systems were connected to the grid through the same distribution transformer and were accordingly considered as a single plant (as also occurred in the former RD 2818/1998).

Nevertheless, this significant remuneration decrease could be avoided if the company accepted the ownership of the transformer. When power generation facilities were involved, the distribution company was not required by law to assume the ownership of the transformer,[34] but might accept it voluntarily, which ultimately

[32] This is one of the main reasons for the atomization of PV energy producers.
[33] RD 436/2004. Article 2. Power definition.

[34] The CNE prevented that the electricity companies could not be forced to bear the cost of the distribution transformers, since the existing regulation rewarded the distribution activity in accordance with the energy demand and its annual increase, and not in terms of extending the grid to meet new production facilities [36].

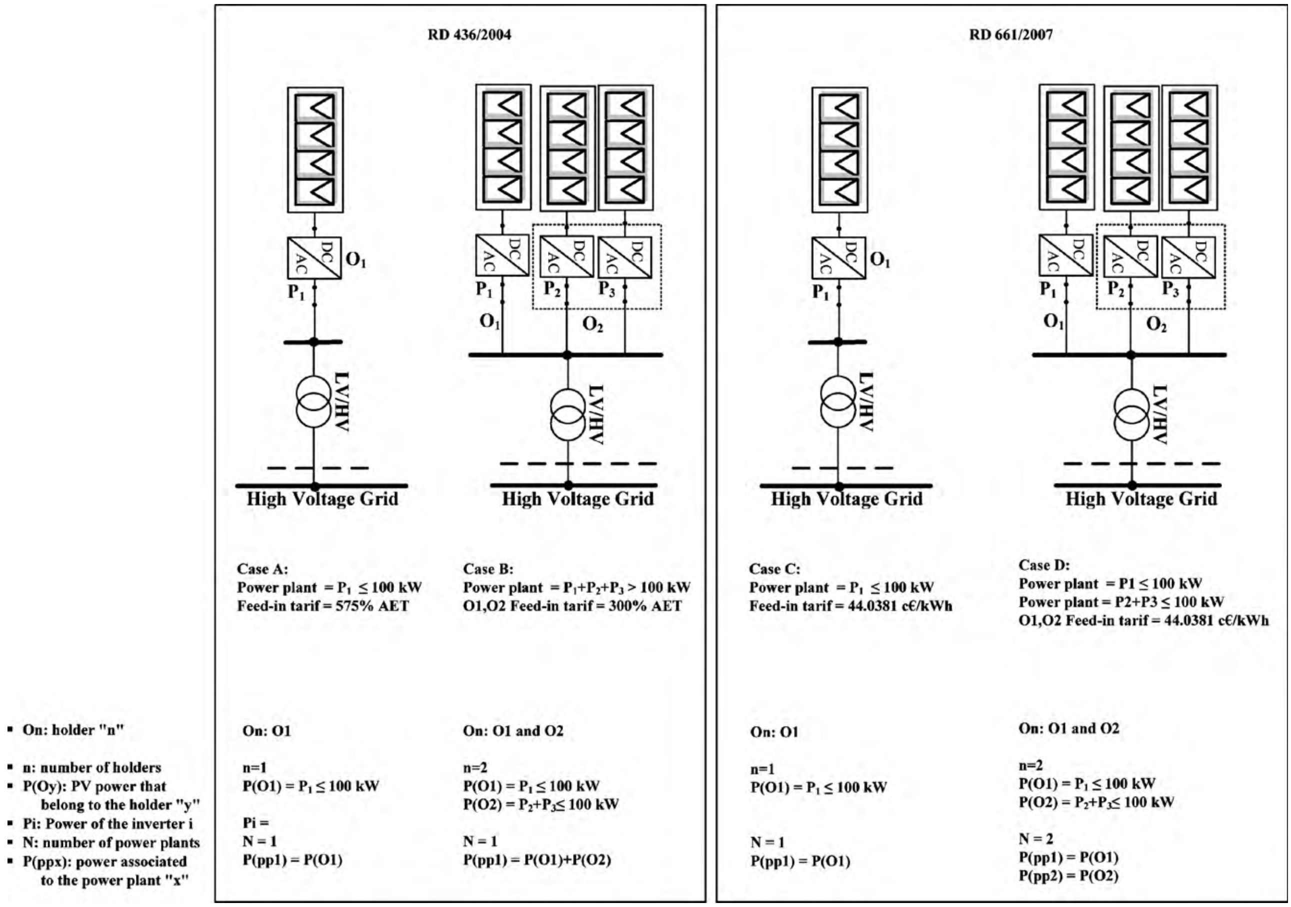


**Fig. 10.** The economic framework and the joint use of grid infrastructure under the RD 436/2004 and the RD 661/2007 solution. Source: self-elaboration.

could substantially alter the retribution of the PV system. In this case, the holders of the different PV systems located in a same place would not be sharing a common distribution transformer belonging to them. As their respective PV facilities ended at the low voltage point previous to the connection to the distribution transformer, they were computed as individual PV systems. This fact would enable them to benefit from the highest FIT provided that the power of each PV installation did not surpass the limit of 100 kVA[35] and that the overall power of any kind of generation facility under the SR that could be jointly connected to the distribution transformer did not exceed half of the transformation capacity that was installed.[36]

In the midst of this controversial situation, the CNE reported [35] that the use of the grid infrastructure was clearly ill regulated by the RD 436/2004. The CNE stated that the fact of sharing grid infrastructures should not entail a change in the FIT value assigned to a PV facility. Despite the various attempts of the CNE to clear up the controversies, the questionable practice of fragmenting the total PV power to install into modules of 100 kW for GCPVS on floor came up reinforced. In fact, the fragmentation practice ultimately acted as a growth engine for the PV sector since it enabled installations on-floor to benefit from the highest FIT [37].

Finally, the RD 661/2007 changed the definition of power of GCPVS, set the economic rewards independent of the joint use of grid infrastructure, and overcame the uncertainty that had existed since the enforcement of the RD 2818/1998. The RD 661/2007 established the entitlement of the PV units as the key factor for determining their power and the subsequent FIT, and considered all PV units of a same holder as a single PV facility, regardless of the joint use of the distribution transformer with PV systems belonging to other holders (Fig. 10, case D).

In brief, the mechanism intended to favour the PV facilities on roof resulted unexpectedly in the promotion of other PV systems typologies. Moreover, the uncertainties that it generated throughout its implementation hindered the initial growth of all PV systems typologies.

## 5. Conclusions

The staggering growth of the Spanish PV sector, particularly in 2008, has rendered Spain the second largest installed cumulative PV power in Europe, after Germany. Surprisingly, though, this growth has been hardly investigated. This paper was thus intended to explain this evolution by focusing on the key growth factors and drivers embedded in the legal, economic and technical framework of the PV energy policy.

To this end, the methodological approach was based on the study of the dynamics of GCPVS growth under control theory principles for the period 1998–2008, which enabled both the identification and the description of the relationships between the control actions effected by the regulatory body and the system's response.

Throughout the whole period as many as five factors or change drivers were identified as having had a major impact on the developmental trajectory of GCPVS. Henceforth, the most remarkable factors are identified and its main consequences inferred.

The first one of such factors was the lack of a clear translation of all the energy objectives into enforceable law. In fact, only one of these objectives followed this path, causing the required multiple-

[35] RD 1663/2000. Article 1.
[36] RD 1663/2000. Article 9.

input multiple-output control structure to be transformed into just single-input single-output. So, the lack of surveillance of the second major target, i.e. the promotion of the GCPVS on roof, prevented the introduction of the corrective actions that would have been necessary to avoid the lopsided development exhibited by the PV sector. As a result, although more than 80% of the PV installations in Spain were located on ground facilities, virtually 100% of them benefited from the tariffs originally thought for PVS on roof, which ultimately hindered the growth of all the PV systems typologies.

A second disturbing factor was the poor control structure in place. In particular, the mechanisms that the control structure had figured out to curb the evolution of the GCPVS proved inappropriate, which contributed to make the system unstable. These circumstances determined that the installed cumulative power target set by law was largely overcome, thus giving rise to all type of ill-fated consequences (e.g. economic, energetic, etc.). Strictly, the control structure was transformed into an open loop system. In this context, although the system output was getting closer to the target, the input (or FIT) kept growing, thus making the system increasingly unstable.

A third relevant factor was the way in which the transition mechanism stipulated by the RD 661/2007 was implemented. The uncertainty about its effective temporal date of entering into force, its a priori one-year duration but later conditioned to not exceeding the 1200 MW of installed cumulative power and the lower subsequent IRR expectations contributed to the avalanche effect experienced by PV systems in the period 2007–2008.

A fourth factor that can be identified as having had a disturbing influence on the development of the GCPVS were the delays that had been introduced into the system by the administrative procedures, the regulatory uncertainty and the grid access. Such delays seriously hampered the capacity of the agents to perceive how the input (FIT) was affecting the evolution of the system as well as the magnitude of its impact.

To end with, when the financial crisis and the economic slowdown became evident, the RD 661/2007 showed up as a bargain for the overabundance of financial capital in search of investment opportunities. The response of the PV industry was immediate. In 2008 it installed as much as five times the capacity of 2007. Still, the fact that some regions had plenty of available land along with the willingness of local governments to actively support PV plants ought to have contributed to the Spanish PV market hype.

Notwithstanding, the facts that should not be underestimated are that in less than a decade the Spanish PV sector has developed proprietary technology, built in innovation capacity, and pushed further its competitiveness edge. Ultimately, it has set the basis for a sustainable RES-E sector. How far it goes will depend on whether the adequate evaluation systems – and, especially, the right control mechanisms – are implemented and the Spanish PV system develops the capacity to learn so that the PV energy policies will not undergo the same mistakes.

In sum, this study has established a qualitative cause-effect relationship between the implemented PV energy policy in Spain in the period 1998–2008 and the actually accomplished targets by the PV sector. The methodological approach used to perform this analysis relies on feedback control systems theory. Hereafter, it is expected that it will prove equally useful to examine the results of the legislative change that took place by the end of 2008.

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